



Multibody Model for Planetary Gearbox of 500 kW Wind Turbine

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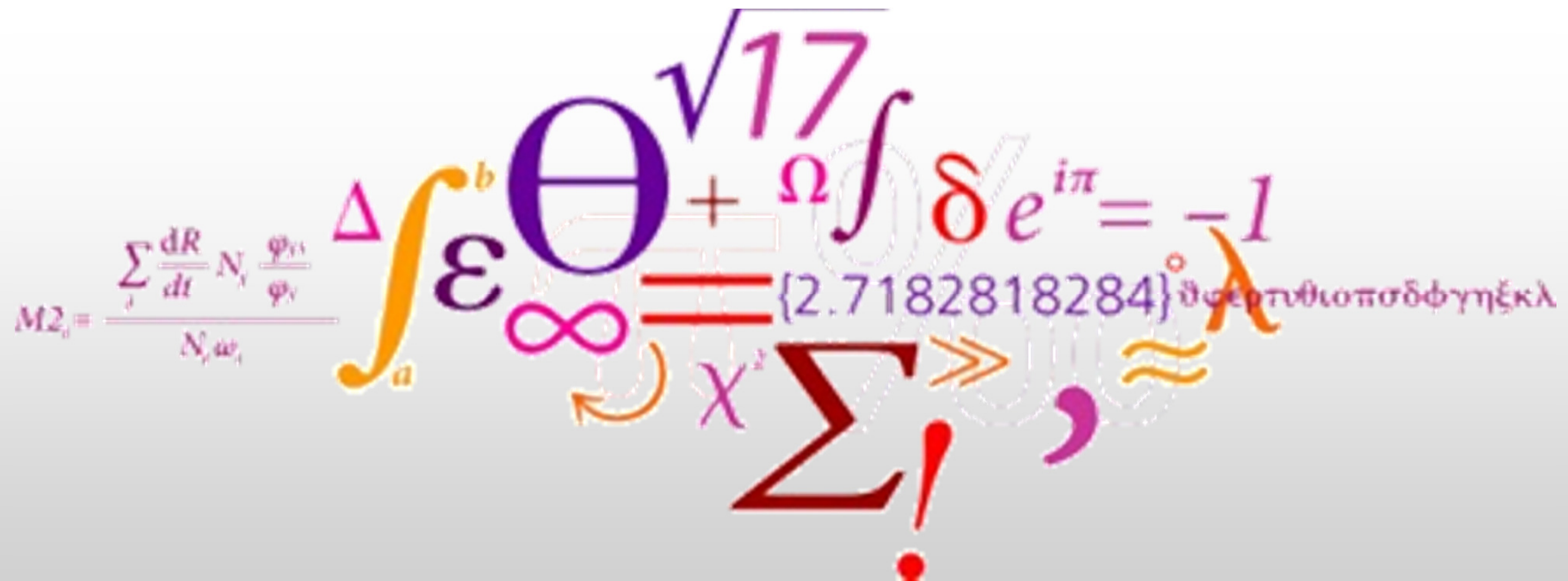
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Multibody Model for Planetary Gearbox of 500 kW Wind Turbine

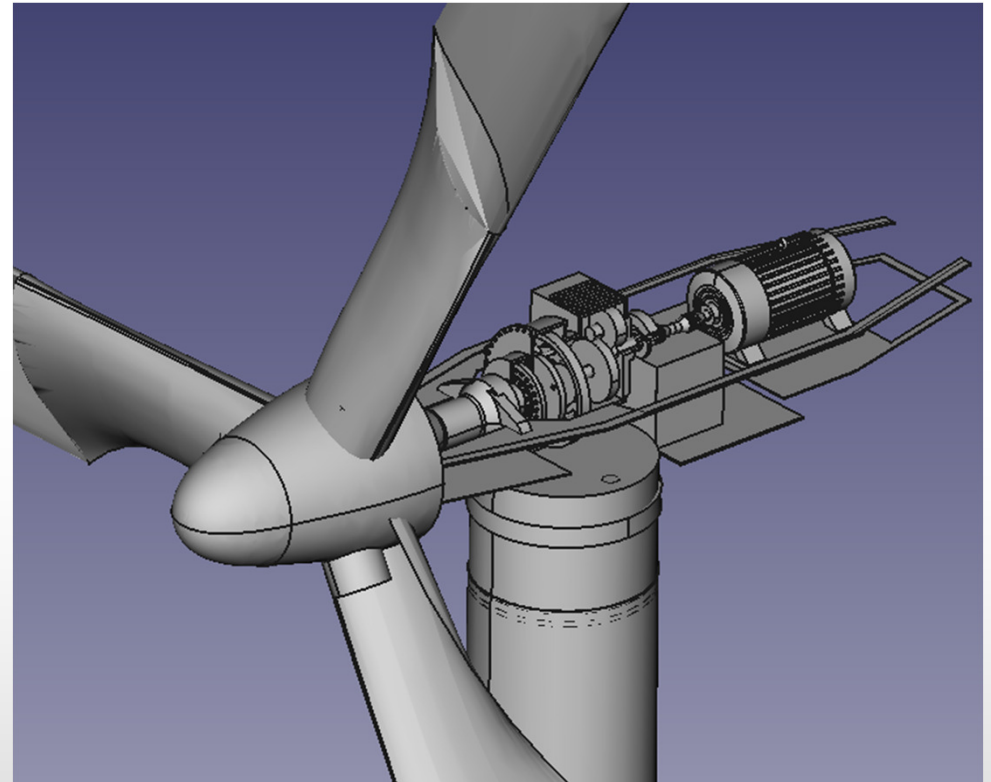
Martin F. Jørgensen



DTU Mechanical Engineering

Overview / topics

1. Introduction
2. Aeroelastic model (FLEX 5)
3. Experiments vs. simulations
4. Multibody model - description
5. Results
6. Conclusions



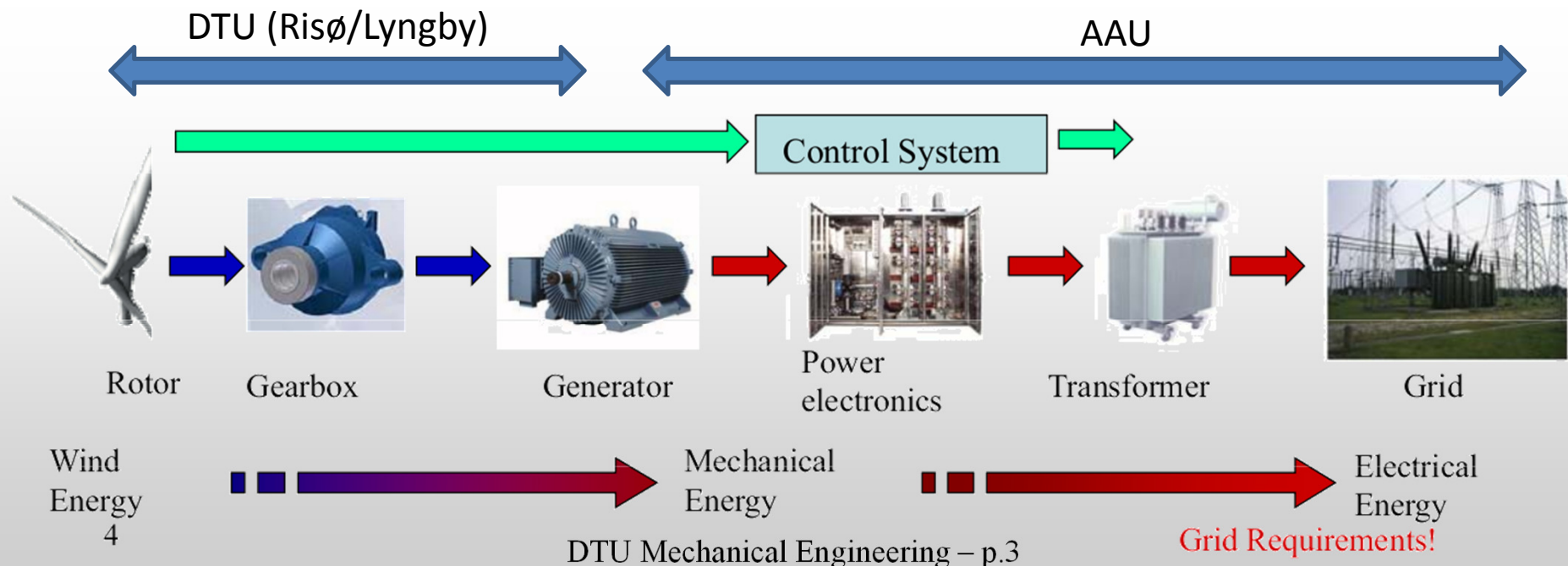
1. Introduction

Objective:

To create a multibody program for modelling drivetrain loads, forces etc on main components such a bearings and all stages in the gearbox.

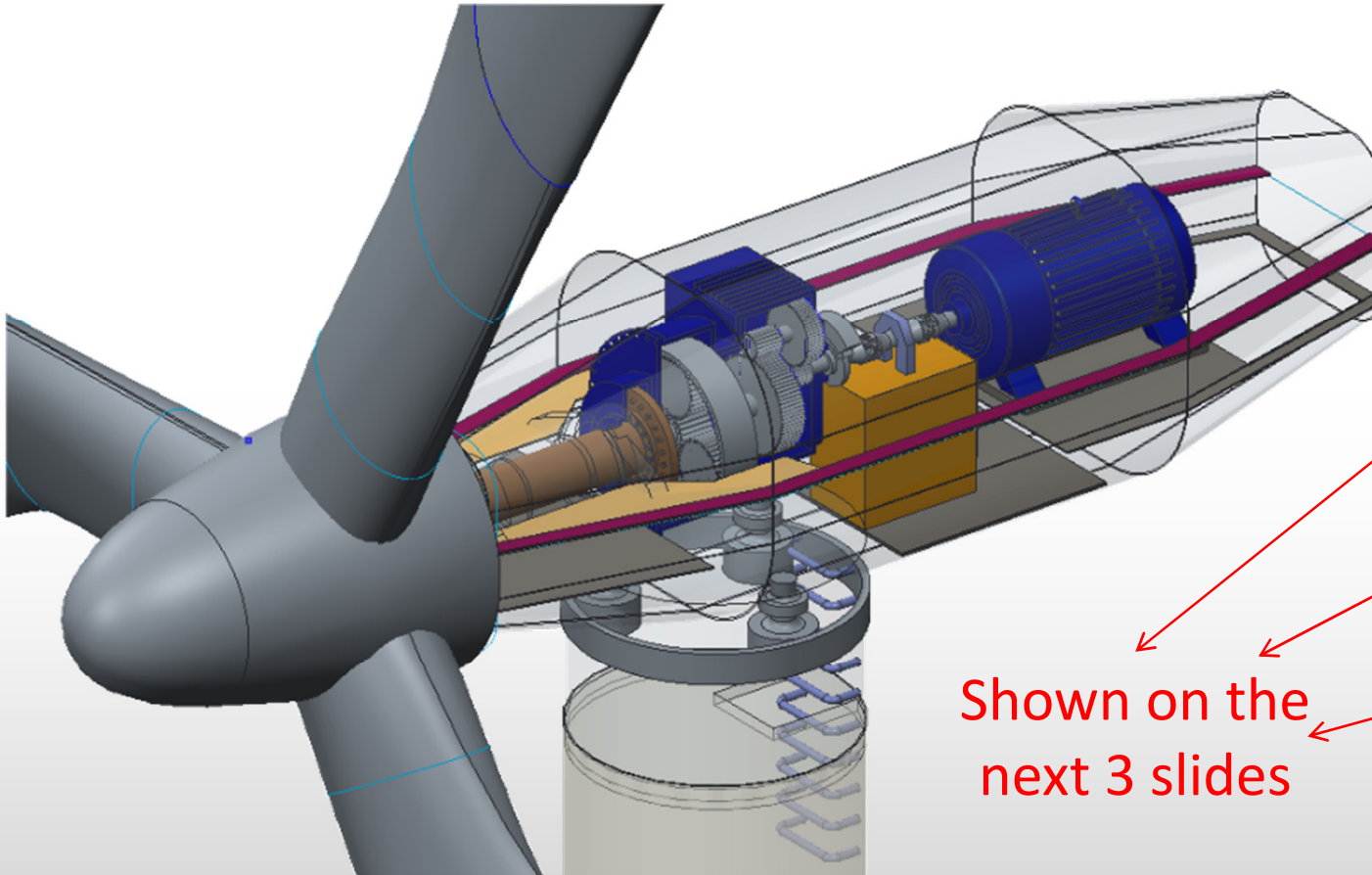
Method:

Matlab code with input for generator and rotor loads from FLEX5, using a complete structural model of the windturbine.



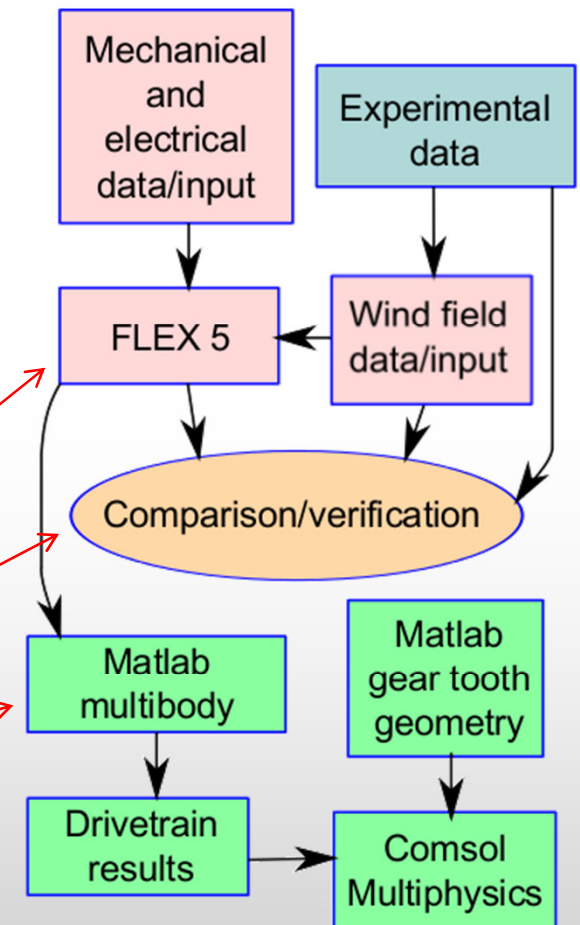
1. Introduction

“Multibody drivetrain model of a 500 kW wind turbine for predicting gear tooth stresses in a planetary gearbox” – methods:



(a) Illustration of rotor, nacelle, main shaft, gearbox (planetary + 2 parallel stages), brake, 500 kW generator, 3 yaw motors etc.

Shown on the
next 3 slides

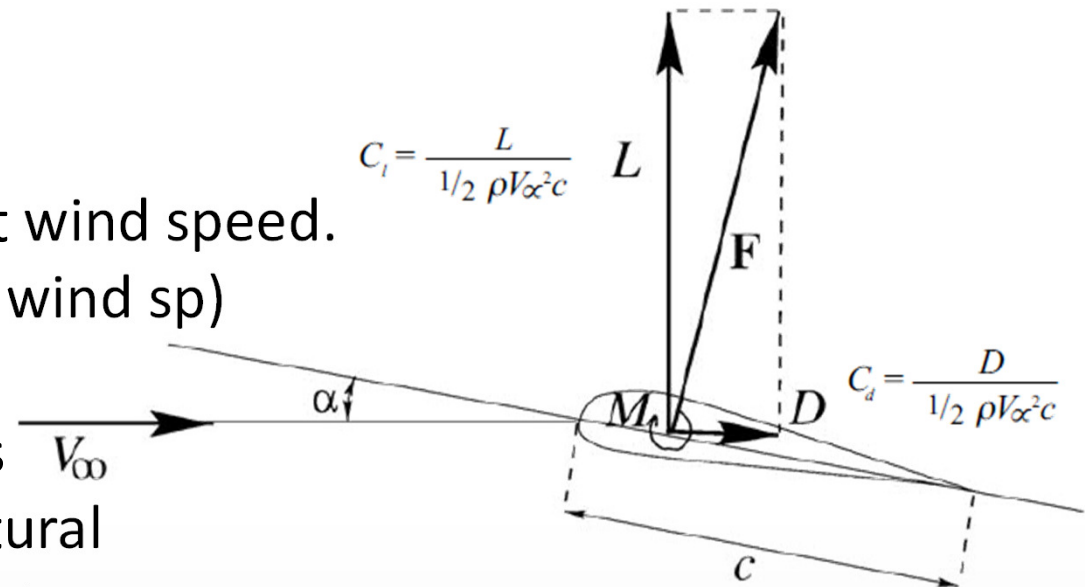


(b) Outline of method used.

2. Aeroelastic model (FLEX 5)

a) Input:

- a) - "Real" atmospheric turbulent wind speed.
- Wind field (based on TI+mean wind sp)
- Blade aerodynamic data: Lift+ Drag coefficients, radial stations
- Elastic properties, mass, structural damping, (bending) stiffness, distances, generator data (mass, moment of inertia, slip, loss/efficiency)



$$\mathbf{M}\ddot{\mathbf{x}} + \mathbf{C}\dot{\mathbf{x}} + \mathbf{K}\mathbf{x} = \mathbf{F}_g$$

b) Output:

Main shaft/generator torque, rotor/blade forces, displacements etc.

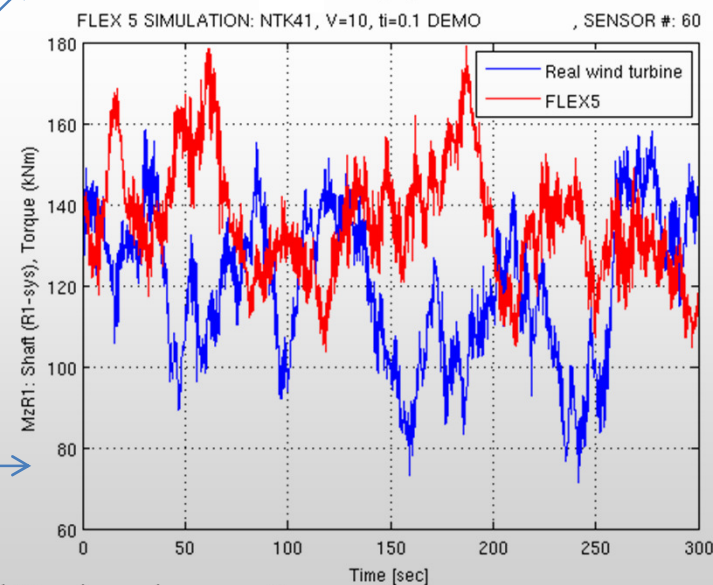
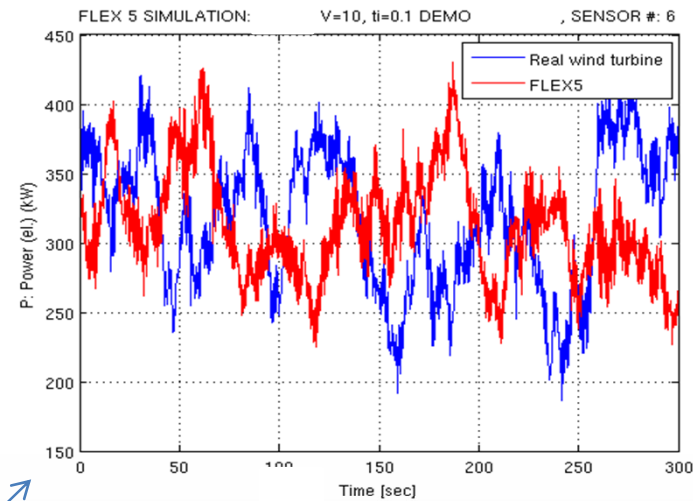
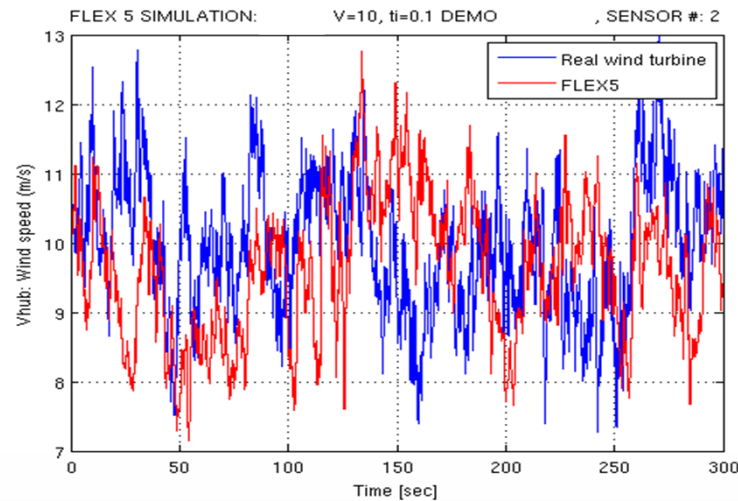
2. Aeroelastic model (+ validation: winddata.com)

FLEX5

Input

FLEX5

Output

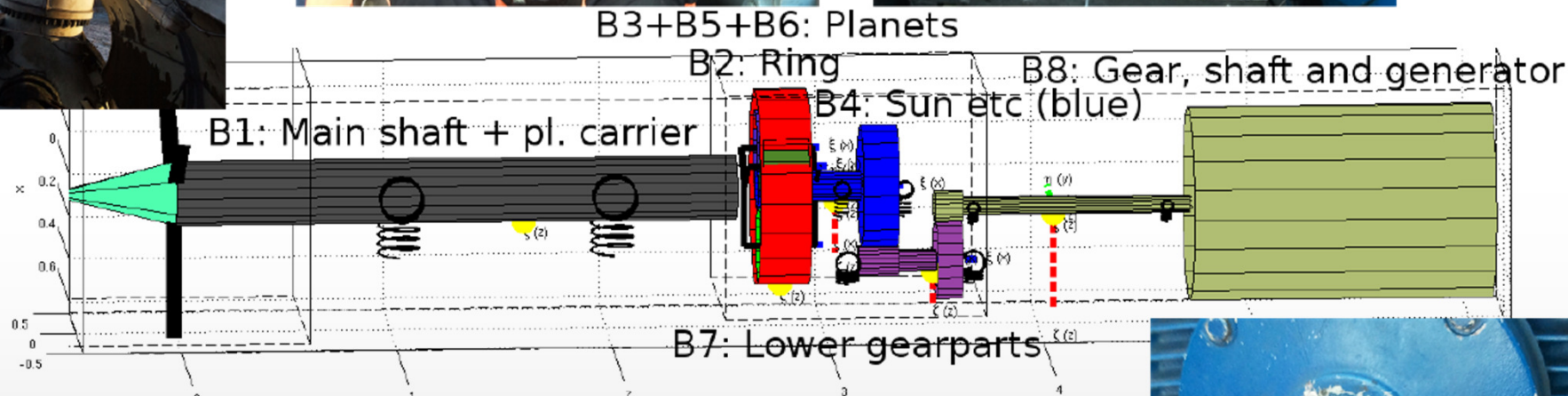
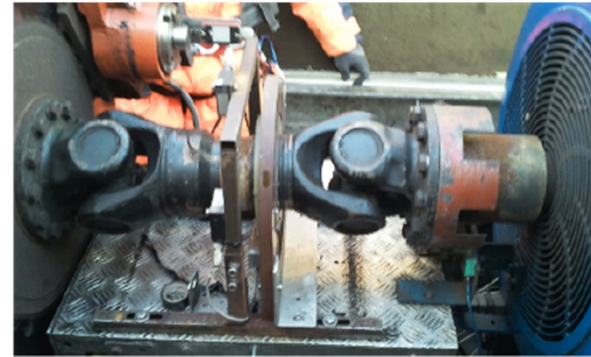
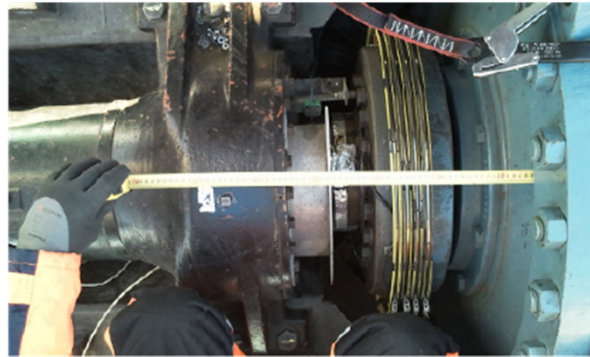


Wind speed (m/s)

Power (kW)

Main shaft torque (kNm)

4. Multibody model – bodies and constraints



4. Multibody model – bodies and constraints

For a constrained mechanical system with m independent constraints

Algebraic constraints $\Phi = 0$ (9.51)

the velocity and acceleration equations are

$$\Phi_q \dot{\mathbf{q}} = 0$$
 (9.52)

and

Diff. eq.

$$\Phi_q \ddot{\mathbf{q}} - \gamma = 0$$
 (9.53)

The equations of motion for this constrained system are as given in Eq. 9.6:

Force equilibrium $\mathbf{M} \ddot{\mathbf{q}} - \Phi_q^T \boldsymbol{\lambda} = \mathbf{g}$ (9.54)

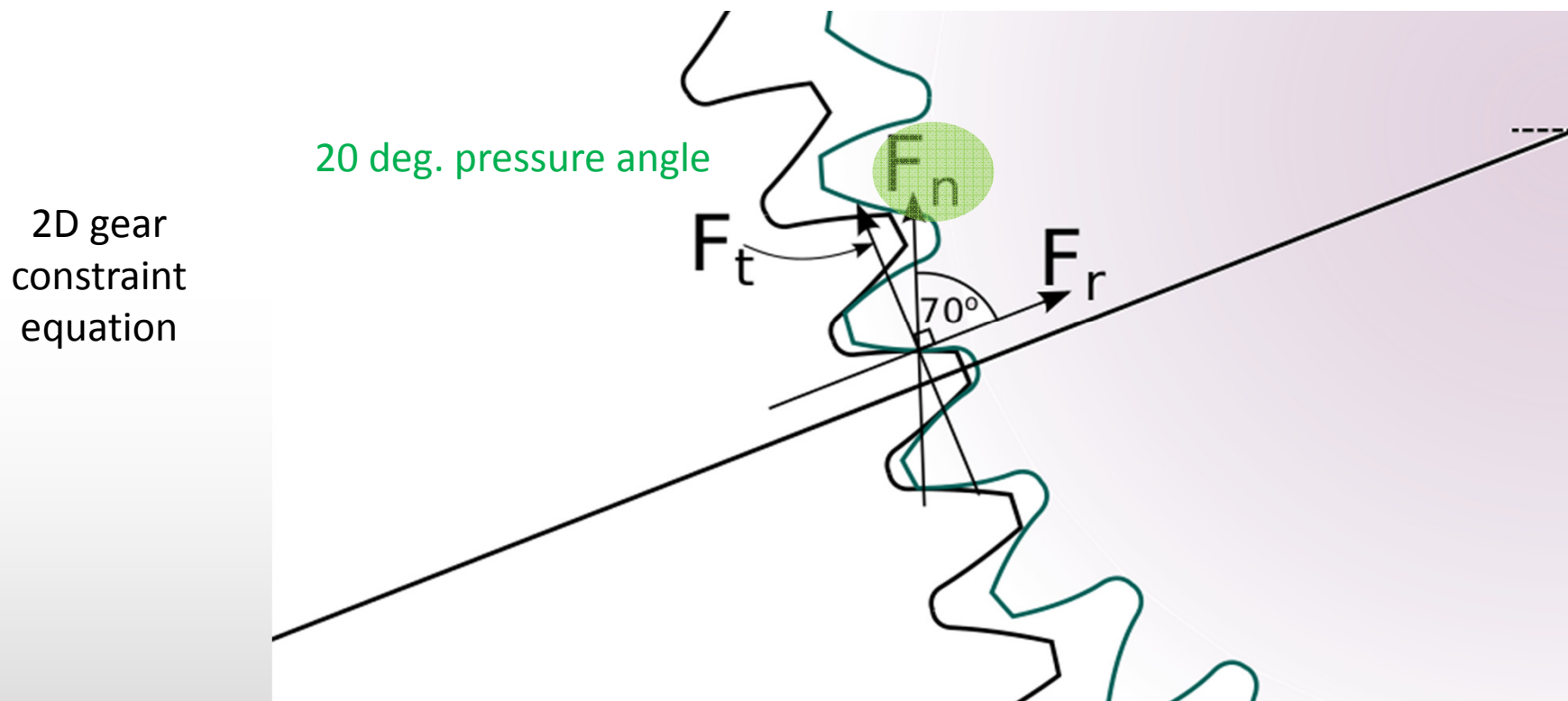
Equation 9.53 can be appended to Eq. 9.54 and the result can be written as

Eq. of motion:
$$\begin{bmatrix} \mathbf{M} & \Phi_q^T \\ \Phi_q & 0 \end{bmatrix} \begin{bmatrix} \ddot{\mathbf{q}} \\ -\boldsymbol{\lambda} \end{bmatrix} = \begin{bmatrix} \mathbf{g} \\ \gamma \end{bmatrix}$$
 (9.55)

Convert 2nd order Initial Value Problem → Two 1st order ODEs:
ODE45 in Matlab to integrate and get velocities and positions

4. Multibody model – bodies and constraints

$$\dot{\Phi} : (A_{70} \cdot v_r)^T \left(\begin{Bmatrix} \dot{x}_1 \\ \dot{y}_1 \end{Bmatrix} + r_{p1}(\omega_1 \hat{v}_r) \right) - (A_{70} \cdot v_r)^T \left(\begin{Bmatrix} \dot{x}_2 \\ \dot{y}_2 \end{Bmatrix} - r_{p2}(\omega_2 \hat{v}_r) \right) = 0$$



$$\ddot{\Phi} : (A_{70} \cdot \dot{v}_r)^T (\dot{r}_1 + r_{p1}\omega_1 \hat{v}_r) + (A_{70} \cdot v_r)^T (\ddot{r}_1 + r_{p1}\dot{\omega}_1 \hat{v}_r + r_{p1}\omega_1 \dot{\hat{v}}_r) - (A_{70} \cdot \dot{v}_r)^T (\dot{r}_2 - r_{p2}\omega_2 \hat{v}_r) - (A_{70} \cdot v_r)^T (\ddot{r}_2 - r_{p2}\dot{\omega}_2 \hat{v}_r - r_{p2}\omega_2 \dot{\hat{v}}_r) = 0$$

4. Multibody model – equations of motion

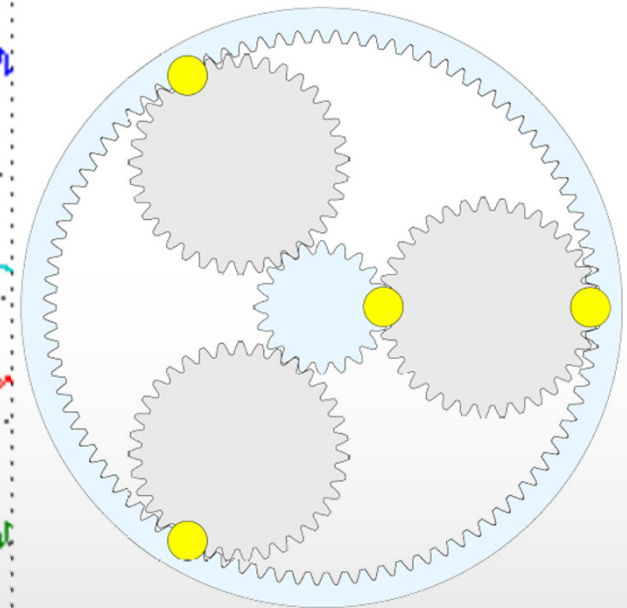
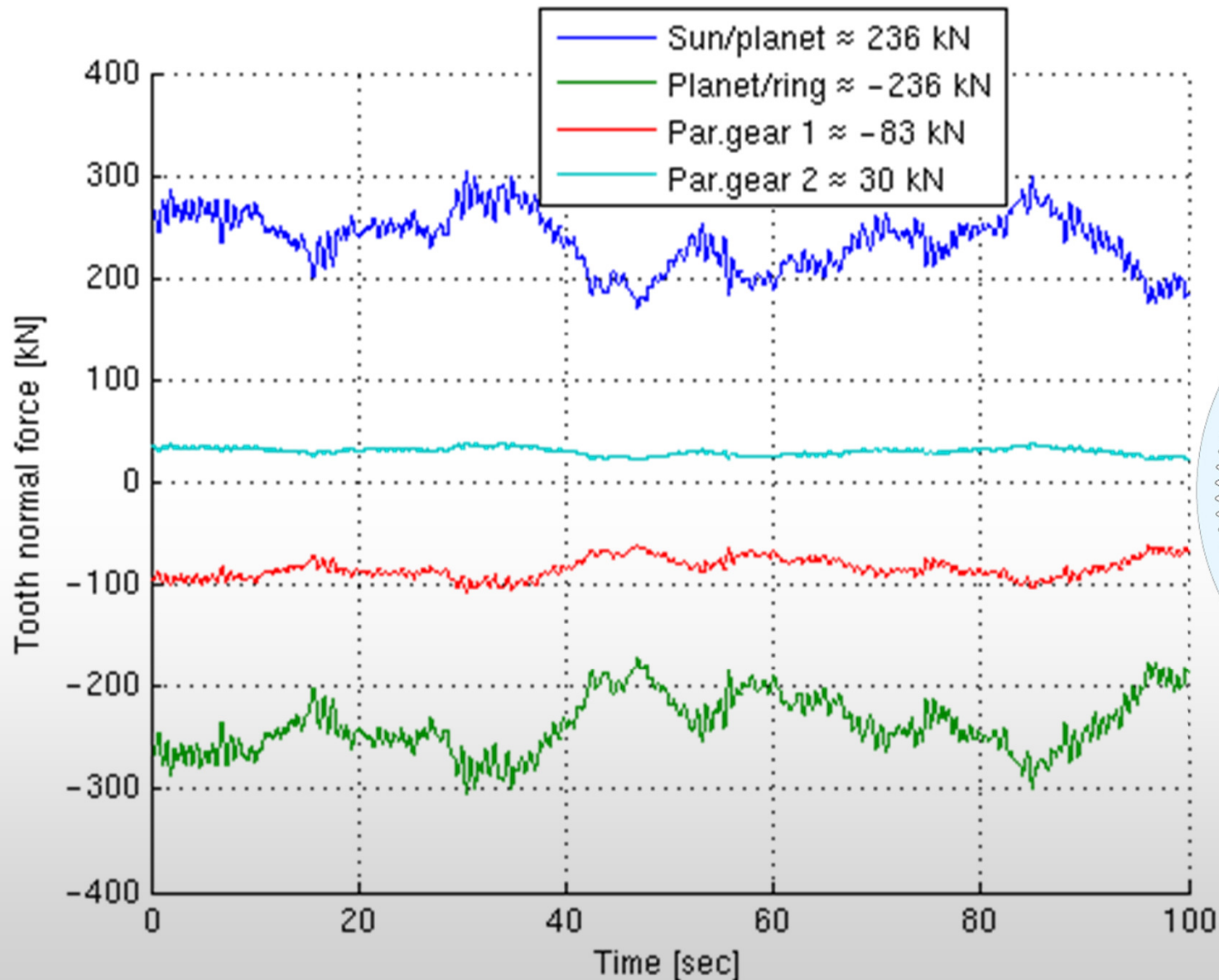
$$\begin{bmatrix} M & \Phi_q^T \\ \Phi_q & 0 \end{bmatrix} \begin{bmatrix} \ddot{q} \\ -\lambda \end{bmatrix} = \begin{bmatrix} g \\ \gamma \end{bmatrix}$$

Reaction forces (in bearings/gear tooth forces etc):

$$M\ddot{q} = \sum F \quad \text{or:} \quad M\ddot{q} = \sum F_{ext} + \sum F_{react} \Rightarrow M\ddot{q} - \underbrace{\Phi_q^T \lambda}_{\text{reaction forces}} = \sum F_{ext}$$

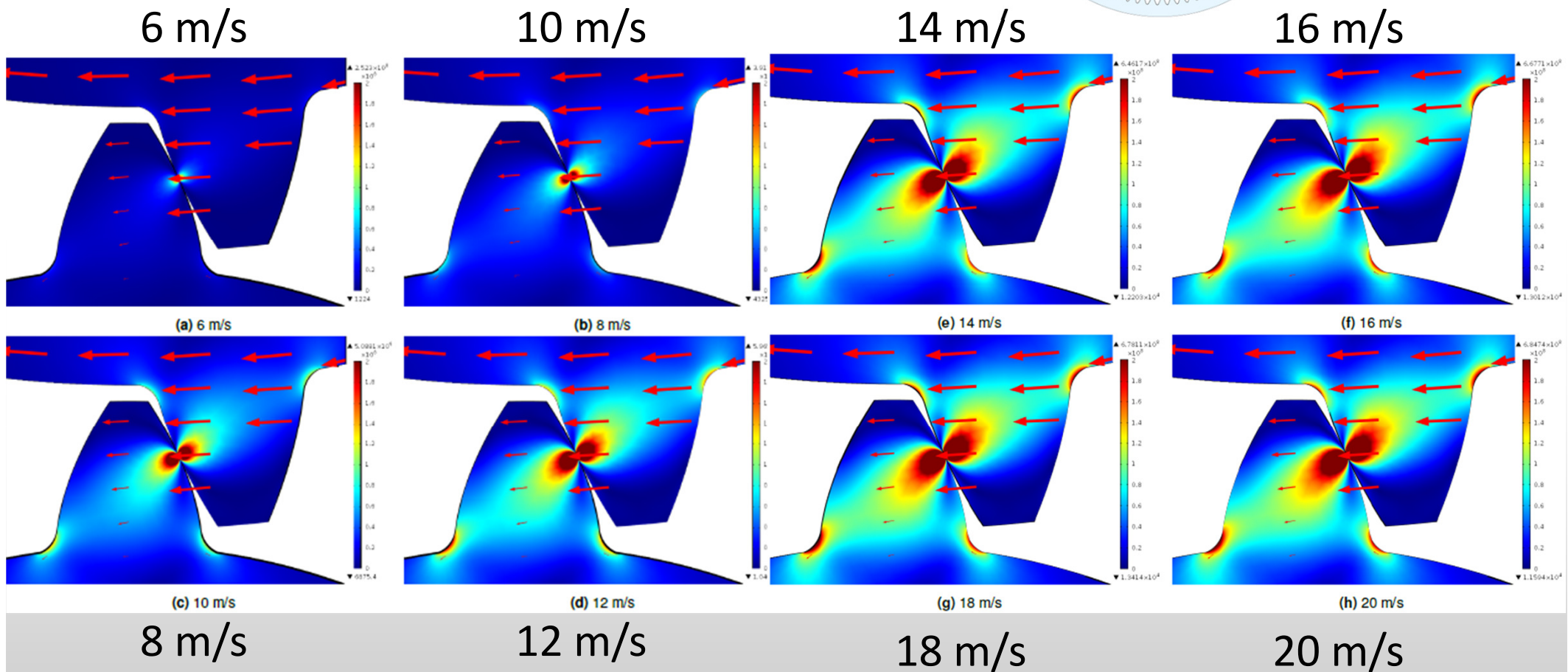
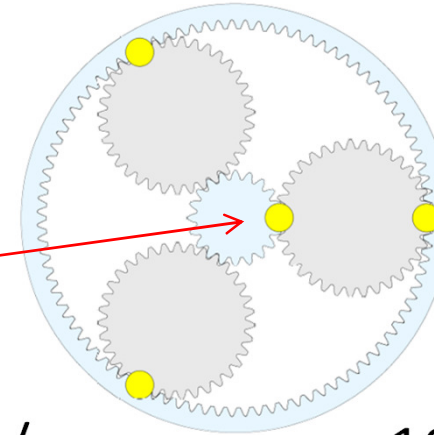
Used for calculating bearing and gear tooth reaction forces and moments

5. Results (gear tooth normal forces)



5. Results

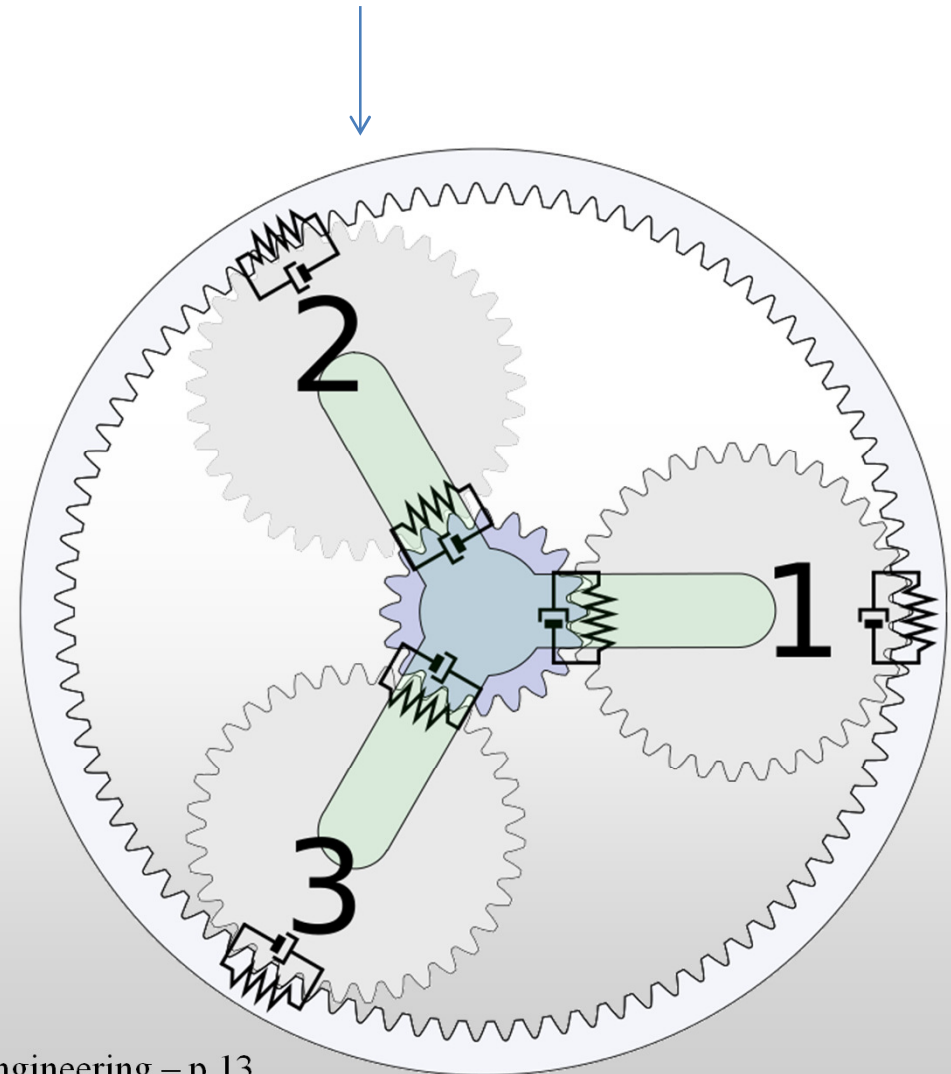
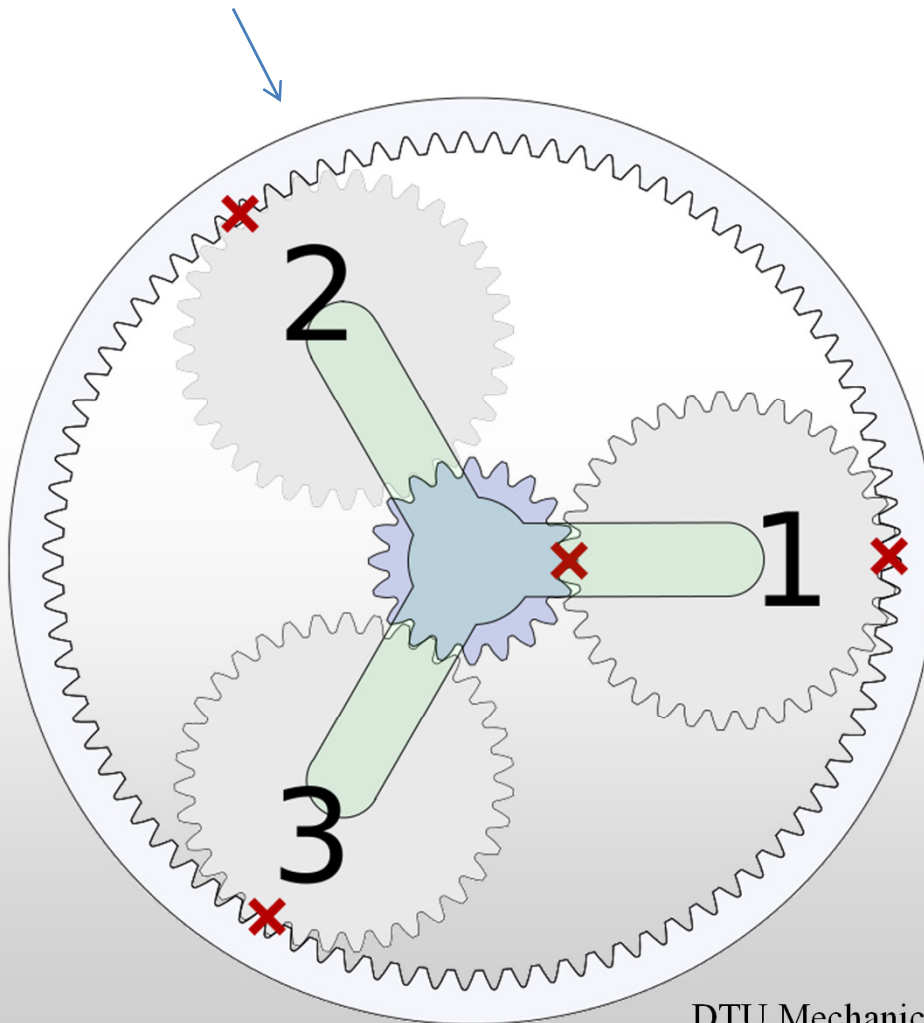
Example: Mean sun/planet gear tooth stresses:



5. Results

Flexible gearbox animation
(work in progress)

Rigid gearbox animation



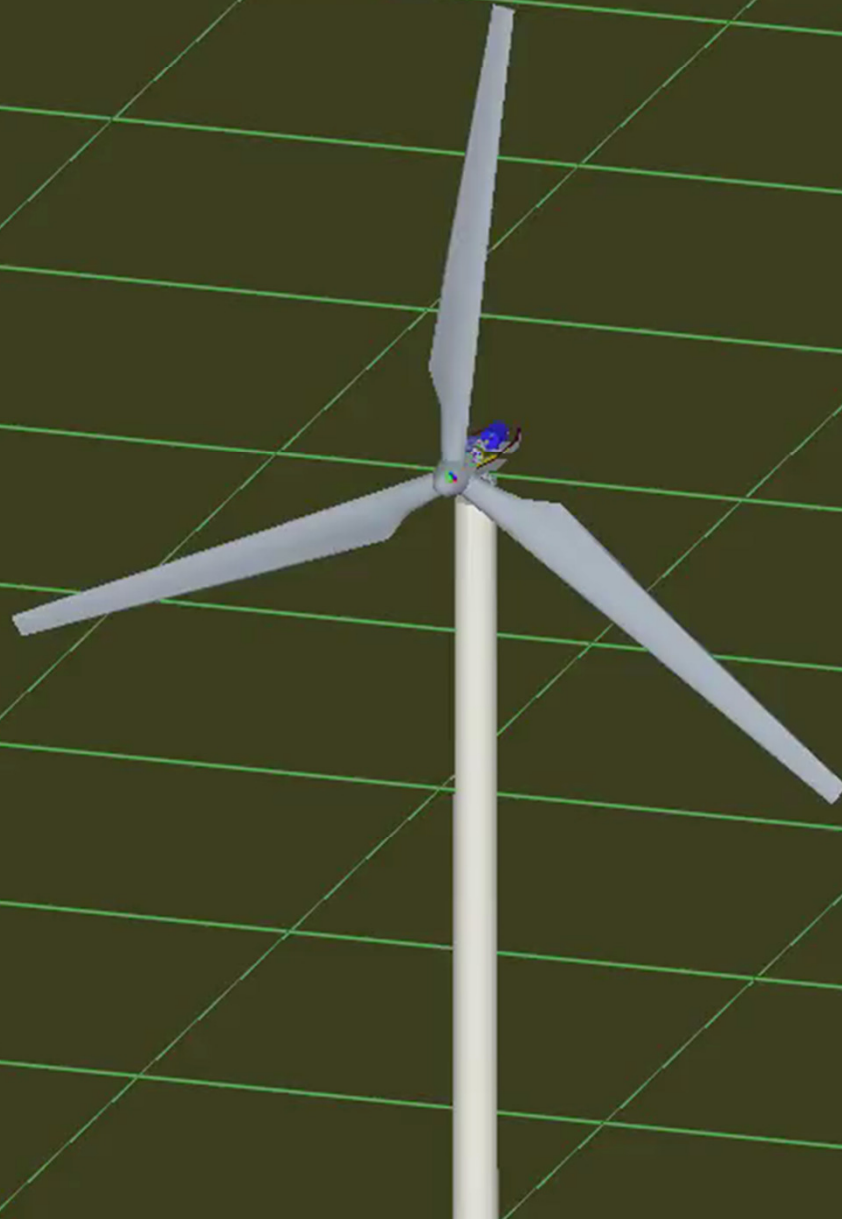
Step: 2072

FPS = 16

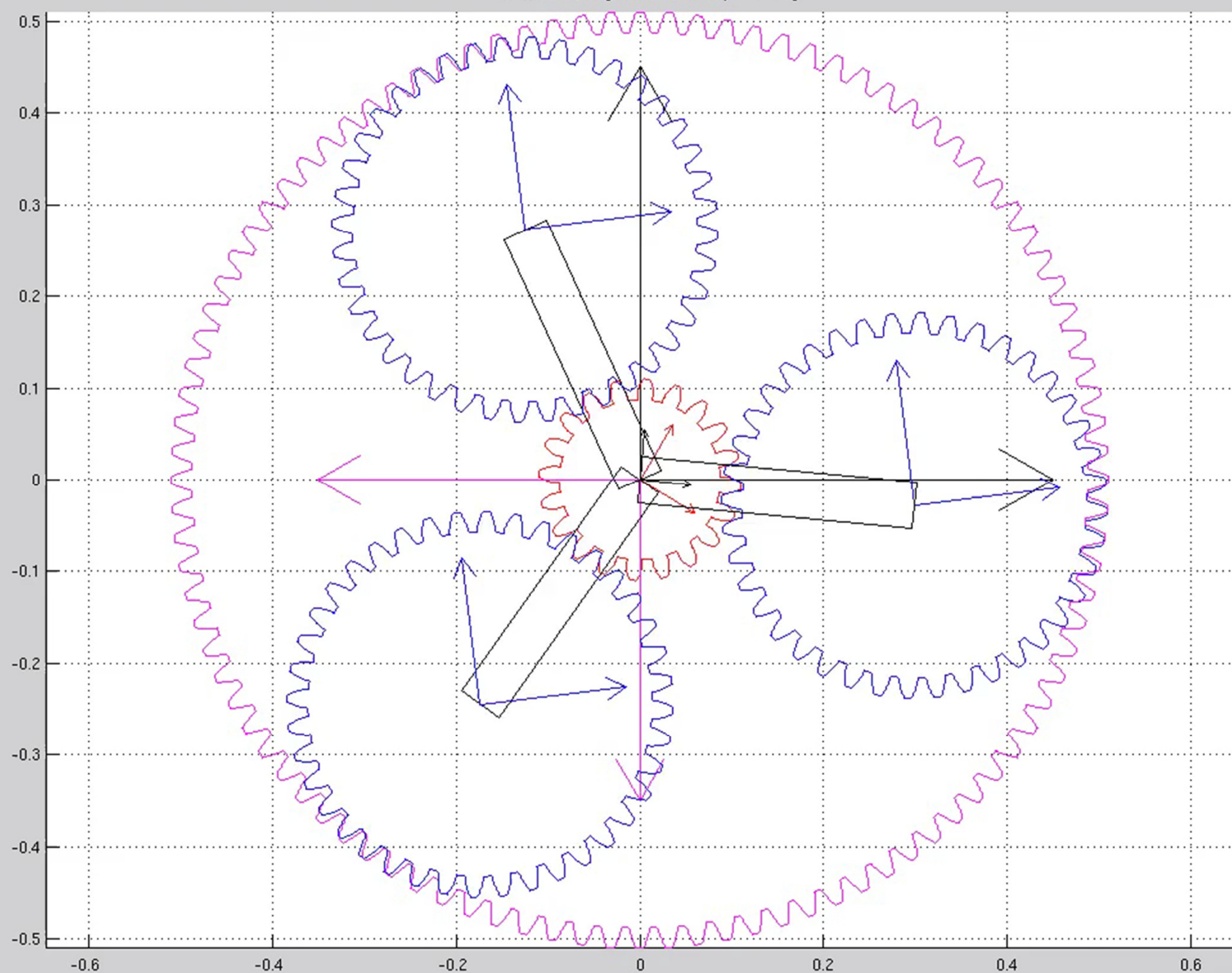
Simulation time: 8.85

Speed: 0

Time elapsed: 130.875



t = 1.5063 sec, angle of carrierBody = -5 deg.



6. Conclusions

- Realistic dimensions and input parameters have been used for modelling a real 500 kw windturbine and gearbox
- Input to multibody code from Flex 5 has successfully been validated using real data (wind speed + strain gauge torque + electrical power)
- A realistic drive-train multibody model has been made
- The multibody program makes it possible to extract e.g. bearing and gear tooth forces and moments (information which cannot be found with Flex 5 without modifications).
- Results from the program can easily be extracted for further analysis using FEM or other tool (e.g. FEM-model of gear tooth stresses made in Comsol Multiphysics).

Thank you for your time

A collage of mathematical symbols and formulas. On the left, a formula for $M2_d$ is shown:
$$M2_d = \frac{\sum_j \frac{dR}{dt} N_j \frac{\varphi_{js}}{\varphi_j}}{N_j \omega_j}$$
 To the right of this is a large purple Θ with a pink ∞ below it. Further right is a yellow integral $\int_a^b \varepsilon$ with a pink Δ above it. In the center, there is a red $+$ and a pink Ω . To the right of these is a red integral $\int \delta e^{i\pi} = -1$. Below the central symbols is a red Σ with a red exclamation mark below it. To the right of the Σ is a purple χ^2 and a yellow \approx . On the far right, there is a purple λ and a string of Greek letters: $\vartheta \varphi \epsilon \rho \tau \upsilon \theta \iota \sigma \delta \phi \gamma \eta \xi \kappa \lambda$. At the top, there is a purple $\sqrt{17}$.